Nuclear Power at Ontario Hydro:
A Case Study in Technological Innovation

F. Tapon
T. J. Osborne

Ontario Economic Council

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NUCLEAR POWER AT ONTARIO HYDRO

a case study

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Francis Tapon
Theodore J. Osborne

81 Wellesley Street East
Toronto, Ontario
M4Y 1H6

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Innovation is the first commercial application of an invention. The innovation process, by bringing the technology up to the standard of best practice, accelerates technical progress. The speed of the adoption and diffusion of new knowledge is what accounts most directly for differences in rates of measured technical development when firms or countries are compared. The 'technological gap' between Canada and the United States is a question of differences not simply between levels of research and development expenditures but also between levels and speed of acceptance of new techniques, which depend on a host of sociological and economic factors. The most formidable barriers to the use of new techniques are the cost of changing existing techniques, the risks involved, ignorance, institutional factors such as governmental regulations, and sociological factors.

Kennedy and Thirlwall (1972) identify two stages in the spread of new technology: the initial adoption; and the rate of acceptance of the new technique within the industry (intra-industry or inter-firm diffusion) and within the individual firm (intra-firm diffusion). This paper concentrates on the intra-firm diffusion of the innovation within Ontario Hydro and throws light on the factors determining that utility's investment in nuclear power. But we also present some observations on the intra-industry diffusion of nuclear plant in Canada, particularly on the speed of its diffusion.[1]

Although more and more studies of the process of technological change, primarily spurred by Mansfield, have appeared recently (such as David, 1971; Globerman, 1975; Griliches, 1957; Mansfield et al., 1971), studies of the diffusion of technological change in the public sector or in regulated industries are relatively rare. The spread of an innovation depends upon the growth of the innovating firm and on the rate of imitation by other firms. These two factors are undoubtedly at work in the private sector, where free-market conditions prevail. However, in the public sector, where both publicly owned and privately owned regulated firms

1 Since we study only one innovation in this industry, unlike Mansfield (1968), we are unable to determine the characteristics that make a firm a technological leader with several innovations.

operate, the pressure to innovate may be less than in the competitive sector, even though the capacity of the public sector to introduce technological change may be greater in the first place. Nelson (1972, 51) remarks that 'in public or non-profit sectors the "expansion of the innovator" mechanism is largely or totally scotched. At the same time it means that little or no spur is put to organizations to adopt innovations; there is no build-up of competitive pressure on the public monopoly.' However, there are some compensations. First, although the incentive to imitate is weakened when the innovating unit cannot or will not expand, at the same time the innovator has no incentive to deter imitation. Organizations that cannot themselves expand and know that others are in the same position gain little by preventing others from adopting their own successful practices. Second, publicly owned firms may be encouraged to innovate more quickly because of decisions made by their political masters for reasons such as national security or a desire to develop national resources. In addition, publicly owned firms with the credit backing of their state, province, or country find it easier to raise the necessary capital to finance expansion. Because of the counteracting influences of the lack of any clear-cut profit-like incentive and the effects of political decisions and enhanced creditworthiness through state backing, we are unable to argue a priori that public ownership retards the diffusion of technological innovations. Therefore, our study of the diffusion of nuclear plants in the public utility industry seeks to test whether in the public sector major technological innovations can diffuse at a fairly rapid rate.

THE INNOVATION

The technology of generating electricity with uranium varies markedly between countries. These differences arise from the fact that countries began developing nuclear technology at different times, from their successes and failures, and from the ratio of government to private participation in each case. To show how these factors affected the development of Canada's CANDU technology, we shall briefly examine the mechanics of nuclear electricity generation. When uranium isotopes (derived by a special process from uranium ore) capture neutrons, heat and more neutrons are released. The idea is to use the heat to produce steam, which can turn turbines and produce electricity. If some of the released neutrons are captured by more uranium isotopes the process is able to recur in a chain reaction. But the

released neutrons travel so fast that the uranium would normally have little chance of capturing them. A 'moderator' is thus introduced to slow down the neutrons, increasing the chances of capture and making a chain reaction possible. The material used as the moderator is the main difference between Canadian and other nuclear technologies.

The American system employs 'light' (or ordinary) water as a moderator. Light water itself captures a significant portion of the neutrons, however, inhibiting the chain reaction. Thus, light-water reactors use enriched uranium - a more highly processed form of uranium - to compensate for the fact that a large proportion of the neutrons are captured. This system was adopted in the United States because enrichment plants built earlier for military purposes were found to have spare enriching capacity available for commercial power applications.

Canada's decision to forgo nuclear weapons meant that if a more efficient moderator (one that captured fewer neutrons) was not used Canada would have either to build expensive enrichment plants solely for electricity generation or be dependent on other nations for the enrichment service. The use of a very efficient moderator, 'heavy water' (or deuterium oxide), is unique to Canadian nuclear power generation and is reflected in the nickname CANDU (Canadian Deuterium Uranium).

Canada's decision to employ heavy water in CANDU reactors has certain advantages and disadvantages:

- Heavy-water production is a complex technology that at first confounded Canadian engineers, but it requires a much smaller investment than enrichment plants.
- Because of the neutron efficiency of heavy-water moderation, such reactors use less fuel. On the other hand heavy water is very expensive to produce. To reduce this cost Canada has experimented in one plant (Gentilly-1) with the use of pressurized light water as the coolant while continuing to use heavy water as the moderator (however, the project has experienced numerous problems).
- Light-water technology was developed for the much larger US market, and its widespread use in the United States has re-assured prospective buyers. Nevertheless CANDU technology will be more readily adaptable to future technological advances and to different forms of fuel as current forms become scarce.

These characteristics of heavy-water production were considered in the early decisions about CANDU technology. They affect costs and reliability and thus CANDU's eventual saleability in Canada and abroad. The choice of heavy-water technology has therefore strongly affected the development of Canada's nuclear industry.

THE NUCLEAR INDUSTRY IN CANADA

The electric utility industry

The development of CANDU technology has been determined primarily by the industrial structure of electric power generation in Canada. The structural characteristics affecting the degree of involvement of individual firms in the research, development, and adoption of any new technology include ownership, market share, relationships with governments, and existing alternatives to the technology.

Table 1 presents the pertinent characteristics of the major electric utilities for each province in 1977. There was direct public ownership of most capacity: 76 per cent was publicly operated and 24 per cent privately operated, including 9 per cent owned and operated by manufacturing firms mainly for their own needs. The two largest producers, Ontario Hydro and Hydro Québec, are publicly owned and supply nearly all their respective provincial markets.[2] Together they account for much more than half of the publicly owned capacity and for more than half of Canadian electricity production. They were also the first two firms to build nuclear plants. Ontario Hydro's commitment to nuclear power is one of the largest commitments of any power company in the world. (Hydro Québec's only nuclear station to have produced electricity is Gentilly-1; owing to technical difficulties it will probably not produce power again, but another nuclear plant is under construction in Quebec.) The New Brunswick Electric Power Commission will begin nuclear production in 1980 and will sell some of its power to the Nova Scotia Power Corporation. In other provinces the availability of inexpensive alternative energy supplies (hydro sites in Newfoundland and Manitoba and coal in Alberta) removes the incentive to exploit nuclear energy; in such cases ownership is irrelevant in inducing

2 Ontario Hydro's regulatory status, the role of the Ontario Cabinet and the Ontario Energy Board, and the links between Ontario Hydro and AECL are discussed below.

TABLE 1

Distribution of capacity of major Canadian electricity producers in 1977

	Ownership status	% of total provincial capacity	% of total Canadian capacity	Hydro % of total firm's total capacity	Fossil-Fueled % of firm's total capacity	Nuclear % of firm's total capacity
Newfoundland			9.9			
Churchill Falls Corp. Ltd	Private	80		100		
Newfoundland & Labrador Power Commission	Public	14		67	33	
Nova Scotia			2.2			
Nova Scotia Power Corp.	Public	100			100	
New Brunswick			3.3			
New Brunswick Electric Power Comm. (NBEPC)	Public	100		27	73	
Quebec			22.9			
Aluminum Co. of Canada Ltd	Private	16		100		
Hydro Québec (including AECL)	Public	84		93	5	2
Ontario			33.9			
Ontario Hydro (including AECL)	Public	95		25	53	22
Great Lakes Power and others	Private	5				
Manitoba			4.5			
Manitoba Hydro	Public	100		87	13	
Saskatchewan			2.6			
Saskatchewan Power Corp.	Public	93		33	67	
Alberta			6.4			
Alberta Power Ltd	Private	11			100	
Calgary Power Ltd	Private	53		17	83	
Edmonton Power Production Division	Public	19			100	
British Columbia			12.9			
BC Hydro and Power Authority	Public	68		85	15	

SOURCE: Statistics Canada (1975-7)

the adoption of the nuclear technology. The resource endowment of a province is clearly important in determining whether or not the nuclear technology should play a significant role in meeting that province's future electrical needs.

Another important characteristic of Canadian electric utilities is their reliance on hydraulic stations. During 1975-7, 72 per cent of Canadian production and 59 per cent of capacity were hydroelectric. In fact, Canadian electric utilities are famous for low-cost hydroelectricity, and installed hydro is Ontario Hydro's cheapest method of production. But the remaining undeveloped hydro sites in Ontario are few and not very attractive economically. Thus, although hydro was for a long time the province's most common form of electrical generation, Ontario Hydro is now embarked on one of the most extensive nuclear development programs in the world, with the aid of Atomic Energy of Canada Limited (AECL), a crown corporation.

Reasons for Ontario Hydro's commitment to nuclear power

To understand why Ontario Hydro became committed to nuclear power, we must examine the demand and supply sides of the market for electricity.

Ontario is a very concentrated energy market. Much of its highly industrialized economic base requires intensive energy use. Because of its subarctic climate, space heating accounts for approximately one-quarter of total consumption. And the great distances between points in the province require substantial inputs of energy for transportation, whether by road, rail, or air. Thus, the per capita consumption of all kinds of energy in Ontario is above the Canadian average and well above the average in most industrialized countries.

Between 1950 and 1970, Ontario's energy consumption increased at an average annual rate of 4.2 per cent (Table 2).

The outlook for the 1980s suggests an increase of 4.6 per cent a year in Ontario's total energy demand. In 1980 total requirements will be 3700 trillion Btu, nearly 60 per cent above 1970. By 1990 total requirements are projected at 5700 trillion Btu, or nearly two and one-half times the demand in 1970. A major new influence in the next decade and beyond will be pollution controls, which tend to increase energy consumption.

Worldwide, Canada stands second (Ontario is slightly below the Canadian average) in the per capita use of electricity. The leading per capita consumers of electrical energy in 1969 were Norway 14 452 kWh,

TABLE 2

Ontario energy demand by end use 1950-90
(trillion Btu)

	Residential & commercial	Industrial	Transportation	Conversion loss and own use	Total
1950	300 (29.4)	330 (32.4)	230 (22.5)	160 (15.7)	1020 (100.0)
1960	380 (26.9)	440 (31.2)	250 (17.7)	342 (24.2)	1412 (100.0)
1970	625 (26.6)	700 (29.8)	394 (16.8)	631 (26.8)	2350 (100.0)
1980	890 (24.0)	1190 (32.2)	640 (17.3)	980 (26.5)	3700 (100.0)
1990	1200 (21.1)	1950 (34.2)	1100 (19.3)	1450 (25.4)	5700 (100.0)

NOTE: Percentages of annual totals in parentheses
SOURCE: Advisory Committee on Energy (1973, I, 8)

Canada 8959 kWh (Ontario 8669 kWh), Sweden 7743 kWh, United States 7644 kWh, New Zealand 4697 kWh. Table 3 shows electricity consumption by market sector in Ontario during 1971.

Demand for electricity in Ontario has been doubling nearly every decade, corresponding to an average long-term annual growth rate of about 7 per cent. This rate of increase is expected to decline in the 1980s. The 1977 and 1978 load forecasts by Ontario Hydro predicted growth rates until the year 1985 of 6.4 per cent and 5.5 per cent respectively. Ontario Hydro's most recent forecast for the period 1975-2000 is for a 3.4 per cent growth rate in the demand for electricity.

Traditionally, Ontario has depended heavily on hydroelectric power. As recently as 1960 Ontario Hydro generated 99 per cent of its electricity by water-power. But the number of hydro sites is limited, and the growth of load requirements forced the rapid development of steam generating capability. Table 4 shows the transition from water-power and the increasing dependence on steam generation.

After forecasting peak demand Ontario Hydro plans its expansion by establishing how much new capacity is required, when it will be needed, what types are most desirable, and where the new plants should be located. A twenty-year planning horizon is necessary, and the system planning

TABLE 3

Electricity consumption by market sector in Ontario, 1971
(percentages in parentheses)

	Billions of kWh
Residential (including farm and street lighting)	16.3 (22.4)
Commercial	10.0 (13.7)
Industrial (including utility plant use)	34.4 (47.2)
Losses and unallocated	12.2 (16.7)
Total Ontario	72.9 (100.0)

process focuses on the forecast load and the alternatives available for generating electricity to meet it. The choice is therefore confined to technologies that are technically and environmentally feasible and cost-competitive.

Assuming the annual pattern of demand discussed earlier, Ontario Hydro estimates that the base-load component (plants operating at more than 55 per cent of peak maximum) of demand will constitute about 69 per cent of total generating capacity, the intermediate-load component (plants operating at between 10 and 55 per cent of maximum peak capacity) about 22 per cent of total generating capacity, and the peak-load and reserve component the remaining 9 per cent.

Ontario has a wide range of energy sources, with about 80 per cent of the supply originating outside the province. In 1950, 22 per cent of Ontario's energy was supplied by oil; by 1970 this proportion had increased to 40 per cent (Table 5). Hydraulic power increased during the 1950s to 25 per cent of the total energy supply, but it has been declining in relative importance in recent years and by 1970 was only 18 per cent. Large thermal generating stations fueled by oil, natural gas, coal, and uranium now make the main contribution to the electrical supply in Ontario. As a result, an assured supply of these fuels at competitive prices has become a crucial

TABLE 4

Primary fuel as a percentage of electricity produced in Ontario

	Water-power	Fossil fuel	Uranium
1960	99.4	0.6	0.0
1970	60.5	37.8	1.7
1980	27.0	44.3	28.7
1990 Moderate nuclear	13.9	28.2	57.9
High nuclear	13.9	14.4	71.7

element in deciding future commitments. Because of the rapid escalation of price and the insecurity of supplies of crude oil, Ontario Hydro is not planning any more large generating stations fired by oil. Likewise, natural gas is now regarded as a premium fuel, which cannot be 'wasted' on producing electricity. As a result Ontario Hydro must choose between coal and uranium to fire its new generating stations.

Coal with a sulphur content meeting environmental standards is available in limited quantities from the eastern United States. Western Canadian low-sulphur coal is plentiful, but transportation and handling costs make it 40 to 50 per cent more expensive than US coal. Other coal sources exist in Nova Scotia and in Ontario at the Onakawana lignite deposits near James Bay, but production and transportation limitations impair their potential. Of all the fuels used by Ontario Hydro only uranium is both indigenous to the province and available in large quantities. For this reason, the utility's long-range expansion program depends substantially on uranium. In addition to the cost and availability of fuel, other factors influence capacity planning, such as the relative costs of building and operating facilities, health and safety considerations, environmental standards, and siting requirements. These conditions will be discussed later.

The choice of the future generating mix for Ontario Hydro is partly based on the comparative economic costs of available technologies. Because of the long lead time needed for large generating stations (sometimes more than eight years for design and construction alone), these comparisons

TABLE 5

Ontario energy supply 1950-90

	Oil (million barrels)	Natural gas (billion cubic feet)	Coal (million tons)	Hydro (billion kWh)	Uranium (tons U_3O_8)
1950	43 (22.1)	-	23 (56.9)	18 (17.6)	-
1960	115 (42.6)	115 (8.1)	13 (22.7)	36 (25.8)	-
1970	184 (40.7)	440 (18.7)	16 (21.3)	43 (18.3)	- (0.6)
1985	206 (33.0)	850 (23.0)	20 (17.0)	40 (11.0)	1310 (15.0)
2000	290 (34.0)	1100 (22.0)	26 (16.0)	40 (8.0)	2500 (21.0)

NOTE: Percentages of annual totals in parentheses.
SOURCE: Ontario Ministry of Energy (1979)

require estimates of operating costs for an additional thirty years beyond construction. Such estimates are naturally very uncertain. Moreover there are non-economic costs to be considered, and we shall examine them in due course.

Table 6 summarizes the comparative quantifiable costs of generating electricity with fossil, hydro, and nuclear technologies.

The costs of nuclear power are attractive despite high capital costs. Fossil-fired electricity, even in 1976, was about 12 per cent more expensive than nuclear electricity. Nuclear and hydraulic technologies have high capital costs and low operating costs. For this reason once constructed they are less susceptible of inflation, and a year-to-year comparison of total unit energy costs between nuclear and coal stations should be increasingly favourable to nuclear power. Indeed, nuclear power costs are relatively inflation-proof, while the costs of coal-fired electricity are expected to rise with increases in the price of coal.

Ontario Hydro has compared the costs, on a 'life-cycle' basis, of four 850 mW coal stations and four 850 mW nuclear power stations. These calculations show that after nine years and over the remaining twenty-one years of operating life of the stations, coal-fired plants have a lifetime cost disadvantage of 65 per cent at a capacity factor of 77 per cent compared to

TABLE 6

Comparative costs of generating electricity by fossil-fuel, hydro, and nuclear technology, 1976

	Generation cost		Transmission and distribution cost		Fuel cost		Total cost	
	$/kW installed	Mills/ kWh	$/kW installed	Mills/ kWh	$/unit	Mills/ kWh	$/kW installed	(Mills/ kWh
James Bay hydroelectric	691	12.47	560	11.02	-	-	1251	23.49
Gull Island hydroelectric	412	7.94	746	15.69	-	-	1158	23.63
Nuclear	739	14.17	332	6.11	($110/kgU)	3.55	1071	23.83
Coal-fired	375	7.19	332	6.11	($35/tonne)	12.00	707	25.30
Oil-fired	308	5.90	332	6.11	($11.85/bbl)	16.93	604	28.94
Gas-fired	308	5.90	332	6.11	($1.50/mcf)	13.50	640	25.51

NOTE: Costs include interest during construction. Delivered costs assume Ontario loads; unit sizes for fossil and nuclear plants are 750 mW. Nuclear capital cost assumes $97 per kilogram for heavy water; nuclear fuel cost includes 1 mill per kWh for waste management, increased safety and environmental measures, and research and development.
SOURCE: Swain et al. (1978)

nuclear plants. This cost disadvantage increases if expensive western Canadian coal is used instead of cheaper American coal. Conversely, larger increases than expected in uranium prices do not significantly increase the total cost of nuclear power relative to coal because nuclear power costs are relatively insensitive to changes in fuel costs. For these reasons, Ontario Hydro believes that future relative fuel price trends will most likely increase the lifetime costs of coal-generated electricity more than those of nuclear electricity. Finally, the use of nuclear power in Ontario has the additional advantage of reducing the province's dependence on imported fuels.

The development and adoption of CANDU technology

In the early 1950s, Ontario Hydro predicted that electrical demand would greatly exceed the feasible hydraulic supply. Problems associated with years of low water flow also demanded solution. Coal-fired generation was therefore begun, though it was significantly more costly than hydro and depended on foreign fuel. These problems, coupled with the natural abundance of uranium in Ontario, led Ontario and the federal government to co-operate in developing a Canadian nuclear generation capability.

The development of CANDU technology can be divided into the following three overlapping phases:

- In an experimental phase different types of reactors - all using heavy water - were built to test such things as types of equipment, overall efficiency, output reliability, and flexibility to changes in specification. The principal task during this period was the development of the horizontal pressure tube reactor, moderated and cooled with heavy water and fueled with natural uranium.
- In an improving phase, once the technology met the necessary criteria for use in production, large-scale plants were built. During this period, continuous refinements were made to an already proven technology.
- In a standardization phase, once the most important refinements had been made and confidence gained in the use of the technology, the chosen form was replicated on existing sites in Ontario and standardized for construction on new sites. Reduced costs and increased reliability were expected to follow. A standard design, based on the Ontario experience, was developed to promote the sale of the CANDU 'package' in Canada and abroad.

We shall now describe the development of CANDU in these phases. We shall also briefly discuss why CANDU sales have not met the expectations of ten years ago.

1 Experimental development of the technology, 1954-72

At the time Ontario Hydro decided to investigate the use of nuclear power,

> a very substantial scientific and development base for heavy-water-moderated, natural-uranium-fueled reactors existed at the Chalk River National Laboratory ... The combination of the CRNL base and the incentive for early nuclear power development in at least one province led to Government of Canada enunciation of a policy under which Atomic Energy of Canada Limited would take the lead in, and support the development of, nuclear power on a cooperative basis with electric utilities having a declared interest ... In 1955, such a plant was committed for design and construction on a joint basis by AECL, Ontario Hydro and the Canadian General Electric Company, roughly on a 70/25/5 per cent funding basis by the three companies respectively. (Smith, 1975, 6-7)

The Nuclear Power Demonstration (NPD) plant on the Ottawa River is jointly owned by Ontario Hydro and AECL, a crown corporation. Seven Canadian manufacturers worked with Canadian General Electric, the contractor and engineer for the Nuclear Steam Supply System (NSSS: the reactor and fueling system). This demonstration plant first produced power in 1962, supplying one-twentieth of 1 per cent of Ontario Hydro's production that year. The NPD was set up primarily as (and is still successful as) an experimental station for testing new engineering developments and training nuclear staff.

In 1959 AECL funded the Douglas Point reactor, the first unit of which became operational in 1967 with roughly ten times the capacity of NPD. Although still small in comparison to the full-scale plants built later, it was large enough to be a prototype for the domestic utilities in Canada. The first Douglas Point reactor also showed the way towards what would later become the implementation process of all CANDU technology: AECL performed the NSSS engineering, and Ontario Hydro, which would operate the station, did the balance-of-plant (BOP) engineering. In the late 1960s, Canadian General Electric built a complete plant for Pakistan, but in 1968 'CGE withdrew from the field of plant engineering to concentrate on the engineering of nuclear power plant equipment' (Foster, 1974, 479).

In all subsequent CANDU installations outside Ontario AECL has performed the NSSS engineering, and an engineering group closely allied with the future owner-operator has performed the BOP engineering. Some

advantages claimed for this procedure are that the research and engineering are carried out by the same group, the NSSS is designed entirely by one group, and the federal government warrants the plant. Canadian government warranty should increase confidence in CANDU in Canada and abroad and makes this system of implementation unlike any other in the world.

In Ontario, where most nuclear plants have been built, Ontario Hydro has assumed project and construction management, all civil and electrical engineering, and the balance of mechanical, instrumentational, and control work. AECL acts as a consultant to Ontario Hydro.

In Quebec AECL performed the NSSS for the Gentilly-1 plant, and Canatom, a Quebec engineering consortium, performed the BOP engineering. Although Quebec obtains nearly all its electricity from low-cost hydro, nuclear technology was introduced into the province in anticipation of its eventual adoption as hydro supply fell short of demand. Gentilly-1, as noted earlier, is an experimental installation that uses boiling light water rather than heavy water as a coolant. It was also built more quickly than any other nuclear plant: construction started in 1968, and the plant began operating in 1972. Lower total capital costs and slightly higher fuel costs were expected, but power has not yet been successfully produced for a prolonged period because of numerous technical difficulties. Since the heavy-water-moderator/boiling-light-water-coolant combination will have been tested at Gentilly-1, this technology could presumably be improved and implemented more quickly in future if necessary.

2 Improvements during full-scale production 1964-78

The basic all-heavy-water technology was first used on a large scale in Ontario Hydro's four units at Pickering near Toronto. Commissioned in 1964, with construction beginning in 1965, the plants were owned and operated by Ontario Hydro and became operational between 1971 and 1973. The total cost was $746 million - nearly twice the capital cost of an equivalent-sized coal-fired station built at that time. Twenty-three Canadian firms and one German firm were the major manufacturers and suppliers of equipment. The opening of the Pickering station increased the proportion of nuclear power produced at Ontario Hydro from one-fifth of 1 per cent before 1970 to about 15 per cent in 1973-6. Pickering has been reliable while producing at about 80 per cent capacity. The lessons it taught were used in improving CANDU.

Pickering became operational too late for the experience gained there to affect the design of the next project - the Bruce Peninsula group of four reactors (again an AECL/OH venture). But design experience at Pickering and the operations at Douglas Point led to some important innovations and changes at the Bruce plant. The length of time from commissioning to operation of nuclear projects puts smaller countries like Canada at a disadvantage in developing a unique technology; in the United States, for instance, many more new projects are operational when new designs are begun.

Construction began at Bruce in 1970. The Bruce development site includes the original Douglas Point station, a heavy-water plant, an oil-fired steam plant for heavy-water production, and a steam supply system from the Bruce generating station to the heavy-water plants. Two more heavy-water plants are under construction. The Bruce units became operational during 1976-9, and by early 1979 they had increased the fraction of installed nuclear generating capacity at Ontario Hydro to over 23 per cent of the system's total capacity. In 1978, 27 per cent of the electricity supplied to Ontario Hydro customers came from nuclear stations. The first four Bruce reactors and Douglas Point together constitute one of the world's largest nuclear electric generating developments.

3 Replication and Standardization (1973 - late 1980s)

Replication. Since both Bruce and Pickering were successful, Ontario Hydro has at each site already begun construction of four more reactors of the same type. The Pickering 5-8 group is expected to become operational between 1981 and 1983 and the Bruce 5-8 group between 1983 and 1986. Together they will approximately double Ontario Hydro's nuclear capacity. The Darlington units 1-4 are designed to have somewhat greater electrical output than Bruce 1-4 because no steam supply is required for heavy water production. They are projected to be operational in the late 1980s. Although very similar to Bruce, the Darlington reactors will incorporate some evolutionary improvements.

Standardization. The Gentilly-2 plant, commissioned in 1973 and due to begin operation this year, is being built beside Gentilly-1, but unlike the first plant it uses only heavy water. Its design benefits from the lessons learned from the use of previous CANDU reactors. AECL is building it as a 'pattern' for future 600 mW plants elsewhere. This relative homogeneity of design results in reduced equipment costs, the spreading of the

large initial costs of research and development over many units, a technical staff that moves from unit to unit, and operators who can assist each other in solving problems. These advantages were expected to lead to national and international confidence in and acceptance of CANDU, which is now a reliable, efficient, and quickly constructed 'package.' New Brunswick Electric Power Corporation already has one plant under construction at Point Lepreau, which is expected to come into operation in 1980. It will supply about 20 per cent of the electricity needs of the Maritimes. Argentina and South Korea are foreign customers of CANDU.

The future of CANDU

Although this program seems to be an ideal way to maximize the returns from the investment in CANDU research and development, sales of CANDU reactors have not only not reached original expectations but now seem likely to fall short of more recent modest predictions. The disappointing sales result from lower worldwide economic growth, discoveries of new fuel reserves in Canada, new restrictions on nuclear use, the competition from light-water reactors, and the lack of a strong marketing organization: 'To be sure, the international reactor market, overwhelmingly dominated by the light-water reactor, is a highly competitive business to which CANDU is not only a late-comer but somewhat of an aberration. Having a good product, probably even the best product, appears not to be sufficient.' (Royal Commission on Electric Power Planning, 1978, 133).

Suppliers of CANDU equipment could build annually four or five plants like Gentilly-2 or one Darlington complex, that is, generating units totalling 3000 to 4000 mW each year. They are now operating at only about 50 per cent capacity with further declines expected. Not only are many jobs being lost but these highly specialized manufacturers may even leave the CANDU industry altogether. This would mean that future expansions of CANDU, when needed, would take much longer because new manufacturers would have to enter the industry.

Since except in Ontario new Canadian generating capacity in the near future will probably be hydraulic or fossil-fueled, suggestions for maintaining demand for CANDU reactors have centred on foreign demand. Two proposals have been seriously considered. One would make Canadian uranium available to purchasers of CANDU units. The other would dramatically increase sales of nuclear power to the United States, thus simultaneously increasing the demand for CANDU reactors and that for

Canadian uranium.

THE DIFFUSION OF NUCLEAR POWER

This section examines the pattern of innovation in the Canadian electric utility industry (intra-industry diffusion) and within a single firm, Ontario Hydro (intra-firm diffusion). An attempt is made to weigh the influence of various factors on the decision of Canadian electric utilities to invest in nuclear power.

Intra-industry diffusion

How rapidly did the use of nuclear power spread from firm to firm in the Canadian electric utility industry? A list of the firms in our sample is given in Table 7. Figure 1 plots the number of firms that introduced the innovation at successive times. Of the thirteen electric utilities in Canada only five had adopted nuclear power by 1978. These were Ontario Hydro, which took part in the financing, design, and commissioning of the NPD generating station at Rolphton in 1957; Hydro Québec, which committed itself to nuclear technology after 1966 with the construction and operation of Gentilly-1 at Trois-Rivières; and the New Brunswick Power Commission (NBPC), which adopted atomic energy in 1972 with the decision to build a generating station at Point Lepreau, New Brunswick. NBPC sold its plant in 1978 to the Maritime Energy Corporation - consisting of NBPC, the Nova Scotia Power Corporation, and the Maritime Electric Company of Prince Edward Island. Furthermore, additions to Canada's nuclear power program planned but not yet committed for installation by the year 2000 are limited to Ontario and Quebec. Installed nuclear generating capacity for Canada in 2000 is projected at 33 000 mW, of which 31 000 mW would be in Ontario and most of the remainder in Quebec. Therefore only firms with one nuclear power plant before 1978 were included in our sample. This simplified the analysis and eliminated electric utilities that were not potential users of the innovation. Without this assumption we would have had to explain the number of firms that failed to acquire nuclear plants during the period of the study. Each utility is listed once at the time of adoption, measured by the start of operation or by the commitment to nuclear electricity represented by the signing of a federal-provincial agreement.

Figure 1 shows the speed with which nuclear power spread through the electric utility industry. About sixteen years elapsed between the start

TABLE 7

Firms in Canada that adopted nuclear technology

Year	Utility
1957	Ontario Hydro
1966	Hydro Québec
1972	New Brunswick Power Commission
1978	Maritime Electric Company
	Nova Scotia Power Corporation

SOURCE: Ontario Hydro

of construction of the NPD generating station at Rolphton and the New Brunswick Power Commission's decision to begin construction at Point Lepreau. A similar analysis of the US electric utility industry reveals that eighteen years elapsed between the Duquesne Light Company's decision in 1953 to build a nuclear plant at Shippingport and the 1971 decision of South Carolina Electric and Gas Company, the last holdout of the major American electric utilities, to commit itself to nuclear technology. A list of the American electric utilities with the date of announcement of their adoption of nuclear technology is given in Table 8. After 1962 nuclear power diffused somewhat more rapidly in the United States than in Canada. Figure 2 shows the adoption pattern for US electric utilities. Indeed, by 1966 when Hydro Québec committed itself to the nuclear technology, fifteen American electric utilities[3] had announced their intention to construct nuclear power plants. In comparison, it took twenty years or more for all the major firms studied by Mansfield (1968) to install such innovations as centralized traffic control, car retarders, by-product coke ovens, and continuous annealing. Thus the type of regulation practised in Canada (and in the United States) may have inadvertently influenced the rate of imitation of the nuclear innovation in Canada (and in the United States).[4]

3 See Table 8. During 1966, the year a federal-provincial agreement led to the construction of Gentilly-1 for Hydro Québec, seven other American electric utilities announced that they too would build nuclear generating stations.

4 The Appendix pursues this analysis by fitting a logistic growth curve to the data in Table 7. We do not stress the intra-industry diffusion process further because our Canadian sample is too small to support a meaningful empirical analysis.

Figure 1: Intra-industry diffusion pattern: Canada

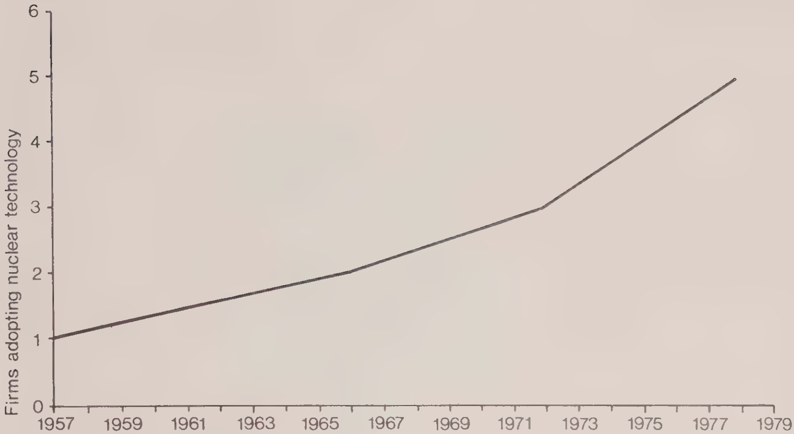

Figure 2: Intra-industry diffusion pattern: United States

TABLE 8

Firms in the United States that adopted nuclear technology

Year	Utility
1953	Duquesne Light Company
1955	Consolidated Edison Company Commonwealth Edison Company Yankee Atomic Electric Company
1958	Pacific Gas and Electric Company Philadelphia Electric Company
1959	Consumers Power Company of Michigan
1960	*Southern California Edison and San Diego Gas and Electric Company
1962	Connecticut Yankee Atomic Power Company
1963	Jersey Central P. and L. Company Niagara Mohawk Power Company
1965	Long Island Lighting Company Boston Edison Company Florida P. and L. Company
1966	Consumers Power Company of Michigan Carolina P. and L. Company Northern States Power Company Virginia E. and P. Company Duke Power Company Metropolitan Edison Company Indiana Michigan Electric Company
1967	Northern Indiana Public Service Company Florida Power Corporation *Wisconsin Group (Wisconsin Public Service Corporation, Wisconsin Power and Light Company, Madison Gas and Electric Company) *Portland General Electric Company and Pacific Power and Light Company New York State Electric and Gas Company Arkansas P. and L. Company Baltimore Gas and Electric Company Pennsylvania P. and L. Company George Power Company *Ohio Edison and Penn. Power

TABLE 8 continued

Year	Utility
1968	*Iowa Electric L. and P. Company, Central Illinois Power Company *Toledo Edison, Cleveland Electric Illuminating Company *Cincinnati Gas and Electric Company and Detroit Edison Company
1969	Alabama Power Company
1970	Louisiana P. and L. Company
1971	Southern Carolina Electric and Gas Company

NOTE: Asterisk denotes public utilities grouped together to acquire the same nuclear plant.
SOURCE: U.S. Atomic Energy Commission (1971a and b)

Intra-firm diffusion

How rapidly has the use of nuclear power grown at Ontario Hydro? We measure the rate at which Ontario Hydro, once it began producing nuclear electricity, proceeded to introduce this method of generating electricity in many new plants in place of other methods (principally coal-fired and hydraulic).

Although Ontario Hydro once relied primarily on hydraulic power, since 1960 it has increasingly turned to thermal generation as the bulk of the economic hydraulic potential of the province was harnessed. Hydraulic power now accounts for less than 30 per cent of total electrical capacity. Table 9 provides a breakdown of Ontario Hydro's generating capacity by primary energy source. Large central thermal generating stations fueled by oil, natural gas, coal, and uranium now account for most of Ontario's electrical supply. Because of increases in oil prices and the uncertainty of oil supply, Ontario Hydro does not plan to build any more oil-fired power plants.

Likewise, natural gas is now regarded as a premium fuel, too valuable for use in generating electricity. As a result of these supply constraints on oil and natural gas, Ontario Hydro's expansion program relies on coal and nuclear generation. The advantage of nuclear power is that of all the fuels used by Ontario Hydro only uranium is both indigenous to the province and available in large quantities.

The present Ontario Hydro power system relies on a well-balanced, diverse mix of generation. For example, in 1978, nuclear and coal-fired plants supplied 27.1 and 25.3 per cent of the province's electricity; hydraulic plants supplied 33.5, natural gas 1.9, and oil 1.6 per cent. Under the committed program and the present load forecast, the best estimates indicate that in 1983 fossil-fired plants will produce about 30 per cent of Ontario's electricity requirements, hydraulic generation will decline to 27 per cent, and nuclear generation will rise dramatically to 40 per cent. When the last unit of the committed program comes into service in 1987, nuclear generation will provide over 60 per cent of the province's electricity requirements. Ontario Hydro has made nuclear power a key element in its system expansion program, on the grounds that to do so will increase the security of fuel supply as well as minimize long-term total unit energy costs, reduce air pollution, and employ Ontario's work force to build generating stations and supply fuel.[5]

At present all ten CANDU heavy-water nuclear generating units in service in Canada are operated by Ontario Hydro. Although the nine nuclear units operating in 1978 represented only about 21.9 per cent of Ontario Hydro's total generating capacity at that time, they produced 27.1 per cent of the electricity supplied to Ontario customers. Table 10, showing the percentages of electricity supplied by source (hydro, coal, nuclear) for the years 1962-78, can be compared to Table 9, which outlines the percentages of generating capacity represented by hydraulic and thermal generation for various years between 1965 and 1978.

The nuclear generating units now in service in Ontario are as follows:

- The 22.5 mW Nuclear Power Demonstration (NPD) station at Rolphton. Canada's first nuclear power plant, it has been operating extremely well since 1962.

5 The Appendix analyses the changes in long-term total unit energy costs brought about by the introduction of nuclear power in Ontario Hydro's generating system.

TABLE 9

Ontario Hydro generating capacity by source (megawatts)

	Installed capacity				Dependable peak capacity				
Year	Hydraulic	Fossil-fueled	Nuclear	CTU & Diesel	Hydraulic	Fossil-fueled	Nuclear	CTU & Diesel	Purchased
1965	5 447 (65.5)	2 764 (33.3)	20 (0.2)	79 (1.0)	4 985 (60.8)	2 619 (31.9)	- -	74 (.9)	521 (6.4)
1970	6 173 (49.4)	5 964 (47.7)	20 (0.2)	342 (2.7)	5 966 (47.1)	5 953 (47.0)	- -	365 (2.9)	386 (3.0)
1975	6 350 (34.2)	9 612 (51.8)	2 180 (11.8)	413 (2.2)	6 156 (33.0)	8 418 (45.1)	2 078 (11.1)	413 (2.2)	1 602 (8.6)
1976	6 386 (30.3)	11 259 (53.4)	2 980 (14.2)	442 (2.1)	6 178 (31.4)	9 575 (48.7)	2 078 (10.5)	432 (2.2)	1 414 (7.2)
1977	6 444 (28.4)	11 259 (49.5)	4 580 (20.1)	451 (2.0)	6 289 (29.4)	10 711 (50.2)	3 558 (16.7)	474 (2.2)	315 (1.5)
1978	6 444 (26.3)	12 259 (50.0)	5 380 (21.9)	451 (1.8)	6 401 (28.0)	11 308 (49.5)	4 298 (18.8)	474 (2.1)	364 (1.6)

NOTE: Percentages in parentheses. CTU means combustion turbine unit.
SOURCE: Ontario Hydro

- The 206 mW Douglas Point Nuclear Generating Station at Tiverton, which began operation in 1967.
- Pickering Nuclear Generating Station 'A'. Canada's first commercial nuclear-electric generating station, it has four identical 514 mW units put in service between July 1971 and June 1973.
- The four-unit, 3000 mW Bruce Nuclear Generating Station A, at Tiverton. Units 1 and 2 went into service in September 1977, unit 3 in 1978, and unit 4 in January 1979. All units have reached their full electrical power levels of 791 mW.

In addition, Ontario Hydro is expanding its system as follows:

- Adding four more 500 mW units at Pickering (Pickering B) for operation beginning in 1981-3.
- Building a second four-unit, 3000 mW station at Bruce (Bruce B) for operation beginning in 1983-6.
- Building a four-unit, 3400 mW station at Darlington, about 25 kilometres east of Pickering, for operation beginning in 1985-8.

Further details about Ontario Hydro's nuclear generating plants are given in Table 11.

We now estimate a logistic growth curve to fit the data in Table 10.[6] P(T) is the percentage of Ontario Hydro's total energy supplied by nuclear power, where T is time measured in years:

$$\log [(P(T)/(1 - P(T))] = \underset{(-14.92)}{-8.11} + \underset{(8.09)}{0.429}\, T \,, \qquad (1)$$

where $\bar{R}^2 = 0.80$, $F = 65.47$, and t-values are presented in parentheses.

Table 12 shows the estimated coefficients for Mansfield's study of the diffusion of the diesel locomotive in the US railroad industry between 1925 and 1959. Comparison of the coefficients of equation (1) with those obtained by Mansfield shows that the rate of diffusion of nuclear power in the Ontario Hydro system has been faster than that of the diesel locomotive in most US railroad companies. The significance of this result should not be overstated

6 The Appendix describes the logistic growth curve, the assumptions underlying it, and its estimation. Also refer to Mansfield (1968, 135-46, 173-85).

TABLE 10

Ontario Hydro's diffusion pattern: growth in nuclear electricity compared to that from hydro and coal sources (percentages of total energy supplied)

Year	Hydro	Coal	Nuclear
1962	69.98	9.16	0.05
3	63.45	18.45	0.21
4	61.12	18.99	0.32
5	62.16	22.39	0.25
6	65.04	19.74	0.31
7	62.61	23.61	0.14
8	59.76	26.72	0.15
9	58.71	29.87	0.13
1970	52.46	32.51	0.18
1	48.25	33.87	4.03
2	47.02	28.17	7.24
3	42.92	22.18	15.81
4	41.59	22.14	14.91
5	39.41	22.84	12.68
6	36.10	23.63	16.46
7	32.44	25.44	23.68
8	33.50	25.31	27.12

SOURCE: Ontario Hydro

because (1) the time periods of the two studies do not overlap, (2) investment in the two innovations represents very different degrees of financial commitment on the part of the firms, and (3) the diesel locomotive innovation replaces an existing technology, whereas nuclear power plants do not displace any hydraulic or fossil-fired plants but rather complement existing resources. Nonetheless, the data are reasonably well approximated by the logistic growth curve, a result also confirmed by Mansfield.

Some determinants of investment in nuclear power

This section considers possible explanations of the diffusion rate of nuclear power in Ontario (Figure 3). Among the variables influencing diffusion patterns in Ontario, we consider the influence of three types: economic, environmental, and regulatory. The Appendix estimates a regression equation in which the influence of economic factors is analysed.

TABLE 11

Status of power reactor licensing in Ontario

Facility (Licensee)	Type and capacity	Status and remarks
NPD Generating Station, Rolphton (Ontario Hydro and AECL)	CANDU-PHW 20 mWe	Started up 1962. Licence duration 29 May 1978 to 30 June 1983. Licensed for full power operations. New arrangement for the calandria spray cooling circuit installed in 1977. Additional design changes to increase the effectiveness of the Emergency Core Cooling System are being implemented or are under review.
Douglas Point Generating Station, Tiverton (Ontario Hydro and AECL)	CANDU-PHW 200 mWe	Started up 1966. Licence duration 5 July 1977 to 10 June 1982. Operating licence: on 25 March 1977, de-rated to 70 per cent of full power pending completion of modifications to the Emergency Core Cooling System.
Pickering Generating Station A, Pickering (Ontario Hydro)	CANDU-PHW 4 × 500 mWe	Started up 1971. Licence duration 30 June 1977 to 30 June 1982. Operating licence: operating at full power with additional operating procedures in effect relating to the Emergency Core Cooling System. These procedures will be replaced with design changes now being installed on the four reactors.
Bruce Generating Station A, Tiverton (Ontario Hydro)	CANDU-PHW 4 × 750 mWe	Units 1 and 2 started up 1976; unit 3 in 1977. Licence duration 21 November 1977 to 30 September 1978. Operating licence: operating at 88 per cent of design full thermal power (producing1 00 per cent of rated electrical power). Unit 4 under construction. Construction licence dated 21 November 1971.
Pickering B, Pickering (Ontario Hydro)	CANDU-PHW 4 × 500 mWe	Construction licence 1974. Start-up expected 1981. Undergoing a review to ensure that overall regulatory requirements are met.
Bruce B, Tiverton (Ontario Hydro)	CANDU-PHW 4 × 750 mWe	Construction licence 1975. Start-up expected 1983. Undergoing a review to ensure that overall regulatory requirements are to be met.
Darlington (Ontario Hydro)	CANDU-PHW 4 × 850 mWe	Site approval granted 9 June 1975. Construction licence application being prepared for Atomic Energy Control Board. Public information program underway. Start-up expected 1986. Undergoing a review to ensure that overall regulatory requirements are to be met

NOTE: PHW means 'pressurized heavy water.'
SOURCE: Royal Commission on Electric Power Planning (1978)

TABLE 12

Estimated regression coefficients for the diffusion of the diesel locomotive among US railways, 1925-59

Railroad	a*	b*	Coefficient of determination
Pennsylvania	- 7.48	0.43	0.92
New York Central	- 5.95	0.35	0.91
Baltimore and Ohio	- 6.10	0.34	0.98
Illinois Central	- 6.21	0.30	0.92
Burlington	- 4.80	0.29	0.99
Missouri Pacific	- 6.94	0.44	0.99
Great Northern	- 4.44	0.27	0.95
Rock Island	- 4.32	0.29	0.87
Northern Pacific	- 5.20	0.27	0.89
Lehigh Valley	- 4.72	0.33	0.79
Nickel Plate	- 6.47	0.34	0.93
Lackawanna	- 4.20	0.28	0.90
Boston and Maine	- 5.01	0.33	0.94
Chicago and Eastern Illinois	- 5.93	0.40	0.73
Duluth, Missabe, and Iron Range	- 9.39	0.40	0.71
Denver and Rio Grande	- 3.96	0.25	0.93
Bessemer and Lake Erie	- 7.18	0.41	0.74
Western Pacific	- 4.79	0.36	0.87
Monon	-11.97	1.04	0.84
Florida East Coast	- 5.52	0.35	0.91
Maine Central	- 6.91	0.45	0.95
Pittsburgh and West Virginia	- 8.50	0.51	0.85
Kansas, Oklahoma, and Gulf	-11.74	0.73	0.45
Seaboard Air Line	- 5.28	0.36	0.97
Virginian	-15.32	0.75	0.57
Chesapeake and Ohio	-10.30	0.59	0.88
Chicago and North Western	- 5.80	0.33	0.99
Norfolk and Western	-30.48	1.35	0.98
Missouri-Kansas-Texas	-11.16	0.73	0.94
Union Pacific	- 5.58	0.33	0.97

SOURCE: Mansfield (1968, 184)
* See regression equation (3), page 44.

Figure 3: Ontario Hydro's diffusion pattern

1 Economic factors[7]

Following Mansfield (1968, Chap. 8) we suggest four determinants of investment in nuclear power, all originating on the demand side of the market. The first significant variable is the profitability of the investment. Other important ones are the ability of Ontario Hydro to finance the investment in nuclear-power plants, Ontario Hydro's size, and the price of debt capital.

The first hypothesis is that the more profitable it is for Ontario Hydro to innovate, the larger the percentage of the firm's energy supply will be represented by nuclear power. Comparisons of the relative merits of alternative energy technologies (coal as against nuclear, for example) are best conducted on a full-fuel-cycle basis - from exploration and mining through waste disposal to ultimate station decommissioning. In the case of nuclear

7 In the Appendix we translate some of the hypotheses presented in this subsection into a regression model and examine it with empirical data.

power, this requires time-series data on 'front-end' capital expenditures for exploration, opening uranium mines, milling, fuel fabrication, and the heavy water program. Finally, investments at the 'back-end' of the nuclear fuel cycle for spent fuel management are also significant. In the case of coal-fired plants, the major front-end costs are the capital costs of transporting western Canadian and Appalachian coal to Ontario Hydro's power stations. The costs of generating electricity can be divided into capital or fixed costs, and variable (operations, maintenance, and fuel) costs. Capital costs and associated interest charges compose the majority of lifetime expenditures on nuclear stations. Capital costs consist of direct costs (materials, equipment, and construction costs), indirect costs (engineering, overhead, and services), contingency costs, and interest during construction. Siting decisions can substantially affect the cost of nuclear power plants. Costs vary from site to site on account of differences in seismic criteria, the natural and physical environment, and availability of cooling water and other facilities.

Variable costs consist of the costs of operations and maintenance, heavy water upkeep, and fueling costs. Including heavy water upkeep, the operations and maintenance costs for 850 mW nuclear stations are estimated by Ontario Hydro to be almost 40 per cent higher than for coal stations of the same size. Moreover, this figure does not fully take into account the additional future costs of security and protecting of nuclear stations. The cost of uranium depends on world prices, on Ontario Hydro's success in using its buying leverage to negotiate lower than world prices for its fuel supplies, and on the uranium policy of both the federal and provincial governments. Relatively high increases in uranium prices do not significantly increase the total cost of nuclear power (relative to coal), since nuclear power costs are relatively insensitive to changes in fuel costs. The large lifetime economic advantage of nuclear power for base load generation remains, even when reasonable estimates of the prospective future costs are taken into account.

The capital cost of a nuclear generating station is, and is expected to continue to be, significantly higher than that of a coal-fired station of the same kilowatt output.[8] The impact of that difference on the cost of nuclear-generated electricity depends on the operating capacity factor and

8 Higher capital costs for nuclear plants arise partly because measures to eliminate air pollution from coal-fired stations are not included in the capital cost of these generating plants (removal of SO_2, and control of NO_X and CO_2).

the proportion of fuel output actually achieved over a period of time. Generating stations with high capital costs and low fueling costs are most economical at high capacity factors. On the other hand, at intermediate loads a station with lower capital costs but higher fuel costs is more economical. The economic competitiveness of nuclear generating stations depends on their ability to operate at high capacity factors, as demonstrated by the Pickering generating station during the past few years. Table 13 illustrates the competitive advantage of nuclear over coal-fired generation in 1976. Pickering and Lambton are similar and contemporary installations; the Lambton generating station is Ontario Hydro's most efficient coal-fired plant. The higher capital cost of Pickering is more than offset by the relatively high fueling cost at Lambton. However, if both stations had operated at a net capacity factor of less than 35 per cent, Lambton would have a lower cost of electricity production than Pickering. Coal-fired stations operating at low capacity therefore have a special role in the future Ontario Hydro system. To the costs of the Pickering station given above could be added 1.2 mills/kWh as a result of the costs for research and development on nuclear technology, decommissioning, and management of waste and irradiated fuel. These added costs reduce the economic advantage of nuclear stations over coal-fired stations for base load operation to about 4.5 mills/kWh.[9] Table 14 gives the capital costs of Pickering A, units 1-4.

The second hypothesis is that the greater Ontario Hydro's borrowing capacity, the easier it is for the utility to finance further expansion of its nuclear power program. Ontario Hydro's capital expenditures on new facilities are large, amounting to $1.4 billion in 1977. A portion of current revenue is used directly for expansion of the power system. But most - 80 to 85 per cent - of the capital construction program is financed through the capital markets with repayment of the debt guaranteed by the provincial government (Ontario has an Aaa bond rating). The net new long-term debt issued for Ontario Hydro in 1977 amounts to $1.1 billion, which will be recovered through future operating budgets when the new facilities begin

9 The fact that the cost per kilowatt for coal-fired production appears to be higher than for nuclear production does not imply that total per unit costs at Ontario Hydro have yet been reduced by the increasing use of nuclear technology. Some estimates presented in the Appendix show that variable costs per unit have been reduced by the adoption of nuclear technology but that total per unit costs have, to date, been relatively unaffected compared to what they would have been had Ontario Hydro used less nuclear energy and more coal.

TABLE 13

Comparative costs of generating electricity from uranium and from coal (1976 $000/kWh)

Cost component	Pickering A (nuclear)	Lambton (coal-fired)
Capital	4.4	1.6
Fueling	1.2*	10.8
Operations and maintenance	1.8	1.0
Heavy water upkeep	0.3	-
Total unit energy cost	7.7	13.4

*This figure includes only Ontario Hydro's expenditures, though nuclear R & D costs have been incurred by other agencies as well. The magnitude of this subsidy of nuclear power should be taken into account when comparing nuclear and fossil-fuel options. The total historical expenditure on nuclear R & D is $1.2 billion, equivalent to 0.8 mills per kWh (Ontario Hydro).
SOURCE: Ontario Hydro (1977)

service. The nuclear component represents almost $24 billion of the $30 billion ten-year capital expansion program. In view of these large sums the provincial treasurer has imposed capital borrowing constraints on Ontario Hydro, which between 1976 and 1978 led to substantial cutbacks in the planned medium-term expansion. In this instance public ownership obviously had a regulatory impact on the speed with which nuclear technology was adopted.

The third hypothesis states that, on the average and with other factors held constant, the larger the firm's capacity relative to the size of the investment, the faster it will introduce the innovation. Indeed, the larger Ontario Hydro's system becomes, the easier it is to use a nuclear power plant. As a result, we can expect the larger utilities or pool members[10] to adopt the new technology faster than smaller utilities or non-pool members, all the more so as economies of scale in nuclear plants are reaped at a higher level of output. In Ontario Hydro's case the evidence to date suggests that plants in the unit size range of 750-850 mW reap significant scale economies. Furthermore, Ontario Hydro asserts that

10 Most electrical utility systems are members of pools. This can greatly influence the size and timing of unit construction.

TABLE 14

Capital cost of units 1-4 Pickering generating station

	($000 1971)	%
Site and improvements	5 100	1
Buildings and structures	73 000	10
Reactor		
Boiler and auxiliary	102 100	14
Fuel	8 700	1
Heavy Water	119 300	16
Turbine generator and auxiliary	66 200	9
Electrical power systems	32 400	4
Instrumentation and control	25 900	3
Common processes and services	32 000	4
Total direct cost	464 700	62
Design and construction		
Operation and maintenance	48 400	6
Engineering	73 600	10
Interest during construction	101 800	14
Contingencies	6 700	1
Other	51 000	7
Grand total	746 200	100
Cost per kWh	$370/kW	

SOURCE: Adapted from Ontario Hydro figures.

the use of 1250 mW CANDU units would capture further scale economies. An increase from 850 to 1250 mW would, in the utility's estimation, decrease unit capital costs by about 10 per cent (even when economic penalties because of lower estimated realiability of units of this size are taken into account). However, no detailed data on capital costs or operating experience are available to test this contention.

The fourth hypothesis is that, other things equal, high interest rates may tend to discourage Ontario Hydro from borrowing and investing in new facilities. This factor must be distinguished from the impact of changes in profitability. In practice, changes in interest rates and changes in profitability will be strongly collinear, and their effects on the speed of adoption of the innovation will prove difficult to disentangle. Changes in

interest rates are important because nuclear plants represent a long-lived and capital-intensive investment and rising interest rates substantially affect capital costs. Ontario Hydro must satisfy the public's demand for electricity in one way or another. However, the firm may choose among several kinds of capital equipment to meet the public's needs. High interest rates may induce Ontario Hydro to choose less capital-intensive equipment such as coal-fired plants. In addition, substantial borrowing in the United States is less attractive than before because of the devaluation of the Canadian dollar.

We have done a statistical analysis of Ontario Hydro's proportion of total kilowatt hours produced by nuclear power as a function of the economic variables mentioned above. This proportion grew from virtually zero in 1962 to 24 per cent in 1976, and 93 per cent of this growth can be explained in the statistical model by those economic factors. Historically, increases in the price of coal and in capacity have significantly raised this percentage: each dollar increase per ton in the price of coal has increased Ontario Hydro's use of nuclear power by 1.6 percentage points. Every 100 000 kWh increase in capacity has led to an increase of 2.5 percentage points.

Increases in the debt/equity ratio and the interest rate on borrowing have offset some of the effects of the other two variables. Each 0.1 increase in the debt/equity ratio has reduced the expected nuclear proportion by 1.4 percentage points. Each percentage point increase in the cost of borrowing has reduced the expected proportion by 2.2 percentage points. Our model predicts that if the debt/equity ratio and interest rates had remained at their 1962 levels the proportion of nuclear power at Ontario Hydro would have been nearly 70 per cent in 1978 owing to dramatic rises in coal prices and demand. In fact, the sharp rises in Ontario Hydro's debt/equity ratio and the cost of borrowing have kept this fraction down to the observed 24 per cent.

2 Environmental factors[11]

Economic factors should not be given undue emphasis. Social and political priorities also greatly influence the decision to invest in nuclear technology.

The first environmental factor that may impede the adoption of nuclear

11 The two environmental factors are discussed separately here for clarity and because we are unable in the Appendix to measure their effects on the speed of adoption of nuclear technology by Ontario Hydro.

TABLE 15

Some available sites for Ontario Hydro nuclear generating stations (megawatts)

	Maximum potential capacity	Generating capacity installed or under construction	Future additional potential
Lennox	7-8 000	2 000 (oil)	8 000
Darlington	8 000	3 400	10-12 000
Wesleyville	5 000	1 000 (oil)	7 000
Bruce	3 000	6 000	12 000
Chats Falls	2 000	-	2 000
Lambton	1 500	2 000 (coal)	1 000

technology concerns nuclear sites and problems related to environmental standards, safety, and waste management. The availability of suitable sites for nuclear power stations limits the growth of Ontario Hydro's nuclear power production. The available sites and their maximum potential capacity in megawatts are shown in Table 15. These sites can accommodate fossil-fired or nuclear power stations, but the added capacity at the larger sites is assumed to be nuclear (i.e. 3400 to 5000 mW per station). Air pollution restrictions place an absolute limit on the use of some sites for fossil-fuel generation unless SO_2 removal systems are installed. Furthermore, if it is necessary to construct cooling towers to limit environmental damage, the potential for increasing the capacity drops by about 50 per cent because of the additional land required.

There are several advantages in situating nuclear plants on the Great Lakes. One is the availability of cooling water. Another is the ease of transporting large pieces of equipment, such as the calandria vessel, by water. Shipment of irradiated fuel from the generating station to a storage centre for irradiated fuel will also need large, heavy transport containers, so that location near the Great Lakes would be advantageous. The geotechnical characteristics of potential sites are a further consideration. A selected site must have a suitable foundation. The soils must be stable, and the site must be free of active faulting. In addition, the station must be designed to withstand earthquakes of a magnitude greater than has

occurred or might occur during the life of the station. Fortunately, most of Ontario is classified as Seismic Zone 0 and Zone 1, although the Ottawa Valley, the St Lawrence Valley, and the Niagara Peninsula are classified as Zone 2.

Finally, rigorous air quality standards affect coal station costs more than nuclear ones because the latter are now designed to limit radioactive releases to a standard 'as low as reasonably achieved,' whereas coal stations do not yet incorporate all technically feasible air emission controls. For example, a decision by the Ontario government to require the use of flue gas desulphurization equipment ('scrubbers') to reduce sulphur emissions from coal-fired power plants could increase the capital costs of these stations by as much as 25 per cent. Operating costs would also be affected because of decreased efficiency.

The second environmental factor that may impede the adoption of the nuclear technology is the availability of hydro sites. Since the turn of the century, 6 million kWh of hydroelectric capacity has been developed in Ontario. Under the present economic conditions and given Ontario Hydro's current operating characteristics, additional sites aggregating about 1.5 million kWh may have economic potential, mainly for peaking power. Some further potential may also exist for pumped storage capacity. The economics of developing hydro sites are usually derived by comparing the cost of developing equivalent fossil-fired capacity. These comparisons are sensitive to the prevailing rate of interest on borrowed funds, construction costs, escalation of prices of labour and materials, and the price of fossil fuels. In addition, Ontario Hydro's past studies show that if transmission costs are not excessive a number of the relatively small undeveloped hydraulic sites will most likely be economic if they are developed for an intermediate to low capacity factor. However, in Canada, only Quebec, British Columbia, Manitoba, and Newfoundland-Labrador have potential hydro reserves that can compete successfully with nuclear power.

3 Regulatory factors

Finally, we consider the influence of regulation on Ontario Hydro and other Canadian electric utilities.

Approximately 80 per cent of the fixed assets of Canada's electric energy industry are government-owned, and government involvement in and support of the electric energy industry is substantial, although regulation of the electric utility sector varies from province to province.

In British Columbia, BC Hydro (government-owned) generates and distributes power. It sets its own rates and is not subject to rate regulation by the British Columbia Energy Commission. However, the Commission has the authority to consider and adjudicate certain complaints against BC Hydro, including charges of undue price discrimination.

In Alberta, private ownership of the electric energy sector is predominant, with 80 per cent of the fixed assets being owned by investors. The Alberta Public Utilities Board determines a rate base and a rate of return for the investor-owned electric utilities under its jurisdiction.

In Manitoba, government-owned Manitoba Hydro is responsible for generating and distributing electric power in the province. The Manitoba Public Utilities Board has an appellate jurisdiction over the rates of Manitoba Hydro but not its operations.

In Saskatchewan, the government-owned Saskatchewan Power Corporation generates and distributes electric power throughout the province. Rates for electricity are set by the Corporation and are not subject to approval by any regulatory agency. The rates are effective upon the approval of the Corporation's Board of Directors, which is appointed by the lieutenant governor in council.

In Ontario, government-owned Ontario Hydro is required to supply power to municipal distributors at prices based on cost. Ontario Hydro sets its own rates; the Ontario Energy Board is not required to determine a rate base and rate of return. In fact, Ontario Hydro is not subject to much regulatory constraint in adjusting electricity rates to reflect rising costs. The provincial utility is empowered to hear and adjudicate complaints that municipal distributors are charging excessive and unfair rates or are supplying power below cost to large users.

Government-owned Hydro Québec controls all production of electricity in Quebec except the generating plants operated by certain industrial organizations primarily for their own use. Hydro Québec itself fixes the rates and conditions for supplying power.

The government-owned New Brunswick Electric Power Commission controls the generation and distribution of all electric power in New Brunswick. However, the Commission is not regulated by the provincial Board of Public Utility Commissioners and itself fixes the price of electricity.

The government-owned Nova Scotia Power Corporation supplies power throughout that province. Its rates are not subject to regulation by the Board of Commissioners of Public Utilities.

In Prince Edward Island, the investor-owned Maritime Electric Company provides direct service to customers, and its rates are regulated by the provincial Public Utilities Commission.

In Newfoundland, the government-owned Newfoundland and Labrador Power Commission supplies electric power throughout the province. The Board of Commissioners of Public Utilities has no authority over the Commission and does not regulate its rates.

We shall now review in more detail the regulatory status of Ontario Hydro and attempt to outline the ways in which it has affected Ontario Hydro's rate of investment in nuclear technology.

Since 1946, the control and supervision of most aspects of the nuclear fuel cycle, the setting of standards and licensing, and health, safety, and security programs in Ontario (and Canada) have been the responsibility of the federal Atomic Energy Control Board (AECB). The Board also accepts and applies international standards in the licensing of nuclear facilities. In an effort to increase the AECB's effectiveness the Trudeau government in 1978 proposed the creation of a new Nuclear Control Board (NCB) to replace the AECB. The responsibilities of the NCB would be to license nuclear plants, set standards, inspect nuclear facilities, make regulations, and hold hearings.

In addition, under The Power Corporation Act, Ontario Hydro must obtain approval from the Ontario cabinet for contemplated acquisition of land and construction of major facilities such as nuclear and heavy water plants. The premier of Ontario appoints Ontario Hydro's chairman, who reports to the cabinet through the minister of energy. There is also an informal relationship between Ontario Hydro's management and the government - which leads Ontario Hydro to co-operate with and provide information on energy matters to the Legislature and to various hearings, particularly the Ontario Select Committee on Ontario Hydro Affairs. In practice Ontario Hydro appears to make its decisions independently and without government interference. (This may change in the future as the provincial government tries to exercise more policy control over Ontario Hydro, because the provincial government is accountable to the public for the actions of its agencies). However, we were told by Ontario Hydro officials that Ontario Hydro could not have gone nuclear so quickly had it not been government-owned. In 1977, reviewing Ontario's energy future, the Ontario government stated that

Uranium-fueled electrical generation is of growing importance for Ontario,

and the effect of withdrawal from the nuclear commitment would be serious in terms of the energy prospects of the Province. Ontario now has no economical and practicable alternative to the use of coal and uranium as fuels for new generating capacity. (Rowan, 1978, 6)

Basically, both Ontario Hydro and the Ontario government consider nuclear electricity to be the cheapest alternative available. This view is reinforced by Ontario Hydro's success with the commissioning and early operation of the Pickering A nuclear generating station.

Ontario Hydro's investment decisions are influenced by the capital borrowing constraints imposed by the provincial treasurer, since 80 to 85 per cent of the firm's capital construction program is financed through bond issues backed by the credit of the Province of Ontario. In 1976 the provincial treasurer perceived that borrowings would be excessive over the short term and decided to limit Ontario Hydro's borrowing for the period 1976 to 1978 to a level well below that originally planned. This led to substantial cutbacks in the planned medium-term expansion program, and several committed projects, including nuclear stations and a third heavy water plant, were deferred.

The most significant provincial legislation affecting Ontario Hydro's nuclear program is the Environmental Assessment Act, which is intended to ensure that environmental standards are respected when new facilities are planned. The Act will apply to all future Ontario Hydro generating stations. (The Darlington station, which was at an advanced stage of planning when the Act was passed, was exempted from its provisions).

The financial and economic implications of Ontario Hydro's nuclear program are reviewed regularly in public hearings by the Ontario Energy Board (OEB) acting in an advisory capacity to the Ontario Ministry of Energy. These hearings are held to review applications by Ontario Hydro for bulk power rate increases. The OEB does not influence Ontario Hydro's investment decisions directly, because it does not review Ontario Hydro's investment program (although in 1974 the OEB was asked to review Ontario Hydro's proposed system expansion to 1983, particularly the need for the additional nuclear stations of Pickering B, Bruce B, and Darlington). The OEB can exercise an indirect influence by recommending that the Minister of Energy not approve any rate increases on the ground that Ontario Hydro possesses overcapacity. This could lead to a slowdown or cutback in the expansion of nuclear power at Ontario Hydro. In addition, every spring the OEB reviews Ontario Hydro's load forecast. On this forecast are based the

plans for expansion of the electric generation and delivery systems. The OEB may recommend pricing incentives as part of a load management program in order to reduce Ontario Hydro's load factors (the load factor is the average load as a percentage of the peak load) and thus reduce the need for system expansion.

Finally, what is the relationship between Ontario Hydro and Atomic Energy of Canada Ltd (AECL)?

In 1952 AECL, a crown corporation, assumed responsibility from the National Research Council for Canada's nuclear research program. In 1954 a task force was formed to design a nuclear power system. This nuclear power division of AECL, established at the Corporation's Chalk River laboratories, was headed by Harold Smith, now a vice-president of Ontario Hydro. The work of the task force led to the design and construction of the prototype 20 mW Nuclear Power Demonstration reactor. In 1958 AECL proposed that a Canadian nuclear power development program be started in order to reduce Canada's dependence on foreign fuels by using Canadian uranium. The reactor core was so designed that Canadian manufacturers could supply most of the parts. Thus AECL assumed the lead in advancing the national development of nuclear power until private sector industries and utilities could develop independent capabilities in the area. The policy of the Canadian government in the nuclear field is based on close co-operation between AECL, electric utilities (principally Ontario Hydro), and the private sector. AECL and Ontario Hydro work together on technical, research, and design matters (personnel are seconded by Ontario Hydro to AECL laboratories for up to two years and partly paid by Ontario Hydro), but administratively the two organizations are completely separate. Until 1964 all Canadian research and prototype reactors were owned by AECL. Until 1973 AECL was the sole supplier of heavy water to Canada's domestic and export markets. AECL continues to provide support, information, and data to Ontario Hydro and manufacturers in the nuclear sector. To meet these commitments AECL maintains research and development establishments at Chalk River, Whiteshell, and Sheridan Park near Toronto. The agency provides engineering services and monitors all nuclear facilities in Canada. In addition, AECL manages the basic reactor design, although over the years, Ontario Hydro has also developed extensive in-house design capability in many aspects of the CANDU system, and Ontario Hydro alone has experience in commissioning reactors. For example, in the case of the Darlington nuclear generating station AECL is

responsible for the design of the reactor cores and fuel-handling systems; Ontario Hydro supervises the overall plant design and the conventional systems; private industry designs and supplies the components.

4 Availability of uranium

Partly economic, partly environmental, and partly regulatory, this factor may encourage a more rapid adoption of the nuclear technology in Ontario. Ontario Hydro's current commitment to nuclear power (a total of twenty reactors at Pickering A and B, Bruce A and B, and Darlington) represents an investment by the Ontario government of more than $14 billion. Of the forecast increase in Ontario Hydro's base-load generating capacity, two-thirds will be provided by nuclear and one-third by coal. Such an ambitious strategy could make Ontario one of the most nuclear-dependent jurisdictions in the world by early in the next century. But that is contingent upon the availability of adequate and secure supplies of uranium.

Canada is rich in uranium. The federal government in 1975 estimated that Canada's reserves represented up to 25 per cent of world resources. The bulk of Ontario's uranium production takes place at Elliot Lake; the only Canadian mine known to be able to support substantial production well into the next century, it contains some 75 per cent of known Canadian reserves.

One uniquely attractive feature of CANDU technology is its use of the natural uranium found in Canada and Ontario. For Ontario, this argument is compelling since uranium is the province's only significant unexploited indigenous energy resource and thus the only one that could afford a degree of energy self-reliance. This fact is perhaps the central strategic reason behind the growing commitment to nuclear energy in Ontario. These optimistic remarks should not mask the fact that the future availability of Ontario or Canadian uranium to Ontario Hydro in the quantities and at the prices needed for a large nuclear program in the 1990s and beyond may be subject to an unpredictable and highly complex set of factors amenable to only slight control by the government of Ontario. The existence of large reserves in Ontario does not guarantee that uranium will be produced at a price acceptable to Ontario Hydro. If uranium increasingly becomes a global, strategic resource replacing dwindling and uncertain supplies of petroleum, the negotiation of future uranium contracts will become difficult and complex. Under new federal guidelines, domestic uranium producers must sell their uranium at world prices. This is consistent with the federal

energy policy requiring domestic energy resources to tend toward international price levels. Consequently, Ontario Hydro may in the future expect to pay for uranium at prices determined by the international market regardless of the origin of the uranium.

We have pointed out that Ontario (and Canada) have enviable quantities of uranium. However, a large proportion of Canadian and Ontario uranium is in categories called 'inferred' and 'prognosticated,' which are uncertain. Therefore, exploration is essential if any of these large, additional estimated quantities of uranium are to be mined. But exploration is extremely risky and requires increasingly large amounts of capital, which may not be entirely available in Canada. The Royal Commission on Electric Power Planning (1978, 139) reports that 'most of the recent large expenditures on uranium exploration in Canada over the past four years (over half this activity was in Saskatchewan in 1977) have come from foreign sources.'

Federal policies determine how uranium deposits will be developed. Indeed, while there are no federal government restrictions on the nationality of the participants financing uranium exploration, once a project has reached the production stage, foreign equity must be limited to one-third of the total assets invested in the project. This policy could inhibit uranium exploration, particularly if foreign investors are uncertain about the export of the uranium. (Canada, for example, in 1978 imposed a year-long embargo on shipments of Canadian uranium to Japan and members of the EEC.)

In September 1974 the federal government, which has jurisdiction over uranium, implemented a policy allowing and encouraging the Canadian uranium industry to continue to participate in the rapidly growing and lucrative world market as long as Canadian domestic requirements were met. Enough uranium must be reserved for domestic use to enable each nuclear reactor operating, committed, or planned ten years into the future to be fueled at an average annual capacity factor of 80 per cent for thirty years; export contracts must be limited to a maximum duration of ten years with contingent approval for five more years; and utilities must maintain a contracted fifteen-year forward supply for all operating and committed reactors. Finally, the new guidelines require Canadian uranium producers to sell their uranium at world prices.

The Ontario government disagrees with this pricing policy and argues that a two-price system for uranium in Canada should be established. Although federal uranium policy appears to guarantee an adequate supply of

uranium to domestic utilities, it has serious limitations from Ontario's point of view. If Ontario were to rely on its own uranium resources, those resources would be insufficient to fuel 30 000 mW of nuclear capacity in Ontario by the year 2000 for the thirty-year lifetimes of the plants. This would mean a growing dependence on uranium from outside Ontario, most likely from Saskatchewan. But even those resources would not be enough to meet Ontario Hydro's requirements, which would exceed all of Canada's potential annual production shortly after the turn of the century.

CONCLUSION

First, the process of diffusion of nuclear power in the electric public utility industry in Canada is quite well approximated by the logistic growth curve. Mansfield (1968), Mansfield (1971), Griliches (1957), and others obtain similar results in their studies of the diffusion of technological innovations in the private sector of the United States economy. Second, it is interesting to note that many of the economic variables that help explain differences in the intra-firm rate of diffusion of innovations in the private sector in the United States and Canada also appear to play a major role in the public sector of the Canadian economy. Finally, the impact of environmental and regulatory factors on the growth of nuclear capacity at Ontario Hydro and across Canada cannot be studied with the usual regression tool because too few Canadian utilities have adopted nuclear technology. Cost-benefit analyses of individual provincial situations would probably be a more fruitful approach and would allow quantification of these important factors.

APPENDIX

We have estimated a sequence of models that reveal the significance of some of the variables that appear to be important in determining the rate of adoption of nuclear power by Ontario Hydro. We employ linear multiple regression, a statistical tool used to estimate the effects of each member of a group of variables (the right-hand variables) on the variable to be explained (the left-hand variable). For each model we also present three additional measures: the t-statistic for each right-hand variable, which indicates whether that variable has significant explanatory power in the model; the correlation coefficient $\bar{R}^2$, which is the percentage of the left-hand variable explained by the model; and an F-statistic, which indicates

whether the entire model has significant explanatory power.[12] The ordinary least squares method of computing regression coefficients is used for all estimations.

Intra-industry diffusion

In order to measure more precisely the rate of diffusion of the innovation, we employ Mansfield's (1968) model of the imitative process. We believe that this model has wide applicability and leads to a correct specification in the case of this innovation. Mansfield's basic premise is that the proportion of potential users of an innovation who are not using the innovation at time T and who begin using it by time T + 1 is a function of, first, the proportion of potential users already using the innovation at time T; second, the profitability of the innovation; third, the size of the initial investment required, and, fourth, other 'unspecified variables.' From that premise, he shows that the growth over time in the proportion of firms using an innovation corresponds to a logistic growth curve:

$$m(T) = n/(1 + e^{-(a + bT)}), \tag{2}$$

where m(T) is the number of firms adopting the innovation by time T and n is the maximum number of potential users of this innovation. We assume that only six firms are potential users. They are Ontario Hydro, Hydro Québec, the New Brunswick Power Commission, Nova Scotia Power Corporation, Prince Edward Island's Maritime Electric Company, and the Saskatchewan Power Corporation. BC Hydro, Manitoba Hydro, and the Newfoundland and Labrador Power Commission are not potential users because those provinces still possess undeveloped and economic hydraulic sites; electric utilities in Alberta can burn oil or coal. In equation, (2), a is the intercept parameter of the logistic curve that measures the 'origin of acceptance,' positioning

12 The higher the absolute value of the t-statistic, the more confidence one has in including the variable in the regression. Similarly with the F-statistic, the greater its value, the more confidence one has that the right-hand variables, taken together, predict movements in the left-hand variable well. For both t- and F-values a critical value (usually associated with a 5 per cent probability of error) is chosen so that if the t- or F-value presented is greater (in absolute value) than this critical value, then the t- or F-value is considered to be significantly large.

the curve on the time scale; b measures the rate of acceptance of the innovation. Mansfield (1968) shows that if one accepts his assumptions the expected value of b for an innovation in a particular industry is a function of the profitability of the innovation, the size of investment required, and the 'unspecified variables.' This specification cannot be tested here because we are dealing with a single industry and a single innovation. Finally, T is time measured in months from January 1957 in Canada and from October 1953 in the United States.

The logistic curve is widely used as a working hypothesis to describe the spread of the innovation once adoption begins. Speed of adoption is measured by the time taken, for example, by an arbitrary number of firms to use the innovation (intra-industry diffusion) or by establishing an arbitrary percentage of a firm's output that must be produced using the innovation (intra-firm diffusion).

The parameters of the logistic curve may be estimated in different ways. Following Griliches (1957), Mansfield (1968), and others, we choose to transform the logistic equation into a linear form and to estimate its parameters a and b by ordinary least squares. We take natural logarithms on both sides of equation (2) and rearrange terms, obtaining

$$\log\ [m(T)/(n-m(T))] = a + bT. \tag{3}$$

OLS estimates are obtained for equation (3) as follows (t-values in parentheses)[13]:

$$\log\ [m(T)/(n-m(T))] = \underset{(-4.97)}{-1.83} + \underset{(5.46)}{0.0122T}, \tag{4}$$

$$\bar{R}^2 = 0.906,\ F = 29.836.$$

For comparison, we present the estimated equation for the American data in

13 Since the 5 per cent critical value for the t-values is 2.78, both the intercept term and time are significant. The 5 per cent critical value for the F-value is 18.5, so that the logistic model explains the Canadian data well.

Table 8[14]:

$$\log [m(T)/(n-m(T))] = \underset{(-11.51)}{-3.76} + \underset{(12.37)}{0.0283T}, \qquad (5)$$

$$\bar{R}^2 = 0.831, \ F = 153.08.$$

The differences in b in equations (4) and (5) can be interpreted as differences in the rate of diffusion of the innovation. Our results indicate that equation (3) represents the Canadian data quite well. The results of these comparisons should be interpreted with caution because of the differences between provincial and state controls over resources. These controls influence the speed of adoption and make a direct comparison of the American and Canadian samples difficult.

CANDU and Ontario Hydro's costs

Utilities choose nuclear technology instead of some alternative form of technology expecting that it will reduce costs immediately or in the future. Presumably nuclear technology reduces operating, maintenance, and fuel costs (call these variable costs VC) but increases capital costs (fixed costs, FC). To examine whether the net results of these two effects has been to reduce electricity costs per kilowatt, we estimated cost relations for the combination of station types chosen by Ontario Hydro over the 1962-77 period. The model used assumes that cost per kilowatt hour produced is a function of wages and salaries per employee W, the price of coal P_c, the price of capital P_k, the level of output produced O, and the extent to which nuclear technology is used P. This relationship should hold for both variable costs per unit of output (VC/O) and total costs per unit of output (TC/O), where TC = VC + FC.

A form of average cost function commonly used in statistical analyses of cost is the Cobb-Douglas function:

$$(C/O) = a\, W^{a_w}\, P_c^{a_c}\, P_k^{a_k}\, O^{a_o}\, e^{a_p P} \qquad (6)$$

14 Here the 5 per cent critical t-value is 2.03, so that both the intercept term and time are significant. The 5 per cent critical F value for this model is 4.17, so that the model is highly significant and explains the data very well.

where P is introduced into the function as a weighted power of e so that if P = 0 (i.e. no nuclear technology was used) then

$$e^{a_p . 0} = 1.$$

As P rises, average costs rise or fall depending on the sign of a_p. Taking logarithms on both sides of (6) we obtain

$$\log(C/O) = \log a + a_w \log w + a_c \log P_c + a_k \log P_k$$
$$+ a_o \log O + a_p P, \tag{7}$$

which can be estimated directly by ordinary least squares. Economic theory suggests the following signs on the coefficients:

$$a_w > 0, \quad a_c > 0, \quad a_k > 0,$$

but a_o can be positive or negative depending on whether costs fall or rise with output, and log a can also be positive or negative. Therefore, we subject a_w, a_c, and a_k to one-tailed tests and a_o and log a to two-tailed tests.

Although we are mainly interested in the effect on total per unit costs to date, we estimate equation (7) twice, first setting C = VC and then setting C = TC. We do this because, if a_P is negative in the VC regression, as expected, this should increase confidence in our model; a_P could be negative or positive in the TC regression depending on whether nuclear technology has increased or reduced per unit total costs. The data used for the regressions are as follows: VC, operating, maintenance, and fuel costs, from Hydro Electric Power Commission of Ontario (1962-77); TC, which is VC plus depreciation and interest costs, from ibid.; W, total wages and salaries paid by all publicly owned electric utilities in Ontario divided by the number of employees, from Statistics Canada (1962-77); P_c, the total value of coal purchased by Ontario Hydro per year divided by the number of tons purchased, from ibid.; P_k, a weighted average of the interest rate on new bonds issued by Ontario Hydro, from Hydro Electric Power Commission of Ontario (1962-77); P, the proportion of total kilowatt hours

sold that are produced by nuclear power, from Table 10; and O, the total kWh produced by Ontario Hydro, from Hydro Electric Power Commission of Ontario (1962-77).

The results are as follows[15]:

$$\log(VC/O) = \underset{(-0.895)}{-1.716} + \underset{(2.16)}{0.057} \log W + \underset{(1.74)}{0.30} \log P_c$$

$$+ \underset{(1.08)}{0.18} \log O - \underset{(-2.32)}{0.96} P, \qquad (7a)$$

$$\bar{R}^2 = 0.986, \; F = 260.3.$$

The signs of the wage and price-of-coal coefficients are positive, as predicted by economic theory, but the price of coal is not quite statistically significant (at the 5 per cent level with a one-tailed test). Output does not have a statistically significant effect on per unit variable costs. In support of the contention that increases in the proportion of nuclear power reduce per unit costs, the coefficient of P, the most significant variable in the equation, is negative.[16] Since the coefficient is virtually -1.0, this means that the current proportion of nuclear power, 0.27, keeps operating, maintenance, and fuel costs 27 per cent lower than they would be in the absence of nuclear power.

To examine the question of overall costs, we run the same regression as above using TC and get the following results:

$$\log (TC/O) = \underset{(1.52)}{3.43} + \underset{(2.0)}{0.06} \log W + \underset{(0.96)}{0.19} \log P_c$$

$$- \underset{(-1.16)}{0.23} \log O + \underset{(0.67)}{0.33} P, \qquad (7b)$$

$$\bar{R}^2 = 0.98, \quad F = 146.9.$$

15 We dropped P_k from the function because its coefficient of 0.02 with a t of 0.07 was statistically insignificant and because its high multicollinearity with the other variables biased the other t-values.

16 The 5 per cent critical value for a_w and a_c is 1.8 and -1.8 for a_p (one-tailed tests). For the F, the critical value is 3.36, so the regression is significant.

Again the signs of the two price coefficients agree with theory, but only wages are significant. The coefficient of output is negative, indicating some economies of scale, but this coefficient is not statistically significant. The coefficient of P now has a positive sign but a very small t value. Thus zero or small negative or positive values are reasonable for this coefficient.

We can conclude that since the effect of investment in nuclear power on per unit variable costs is significantly negative and the absolute value of the effect on average total costs is very small, then the effect of these investments on depreciation and interest costs must be strongly positive. Thus our results confirm the notion that Ontario Hydro's investment in nuclear power has raised capital costs and lowered operation, maintenance and fuel. This conclusion is not surprising since it merely reflects the technical nature of nuclear power plants. But it is important to note that our empirical estimates suggest that nuclear power has not yet reduced the total cost per kilowatt hour of electricity, everything else equal.

These results can be criticized as biased, because P is actually an endogenous variable, so that ordinary least squares yield biased estimates of the a_p coefficient. Future research along these lines would bring together equation (8) below and equation (7) and estimate them jointly by more sophisticated econometric techniques that correct for this bias.

Economic determinants of investment in nuclear power

Our discussion of economic influences on investment suggested that the degree of use of nuclear power (call this P as above) depends on the profitability of investing in nuclear power Π, borrowing capacity (represented here by the debt/equity ratio D/E), the size of the firm S, and the cost of borrowing P_k. These hypotheses can be written

$$P = f\,(\Pi,\ D/E,\ S,\ P_k). \tag{8}$$

The profitability of investing in nuclear power depends on coal prices, uranium prices, and interest costs on both coal and nuclear plants. Since interest costs are included in the model (P_k) and uranium costs were unavailable for the full period, we need to add only the price of coal (P_c) as the remaining determinant of Π. Therefore, assuming linearity, equation (8) can be written

$$P = b_o + b_c P_c + b_d D/E + b_s S + b_k P_k. \tag{9}$$

The coefficients in equation (9) are expected to bear the following signs:

$$b_c > 0, \quad b_d < 0, \quad b_s > 0, \quad b_k < 0.$$

The data used for P, P_c, and P_k are the same as above. S represents Ontario Hydro's total generating capacity, from Hydro Electric Power Commission of Ontario, 1962-77, and the debt/equity ratio is computed from Ontario Hydro's annual reports (ibid.). As above, the data are collected for the 1962-77 period.

Again, we report t-statistics in parentheses below each coefficient:

$$\underset{(1.52)}{P = 0.150} + \underset{(2.30)}{0.0156P_c} - \underset{(-2.20)}{0.4D/E} + \underset{(5.89)}{0.0000253\ S} - \underset{(-2.93)}{0.0224\ P_k}, \tag{9a}$$

$$\bar{R}^2 = 0.93, \ F = 50.56.$$

All four variables are statistically significant (the 5 per cent critical value for t is 2.2 or -2.2), as is the entire regression (the critical F-value is again 3.36). The signs of the coefficients are all as postulated. These results generally support the hypotheses we presented when considering economic factors.

Advisory Committee on Energy (1973) Energy in Ontario: The Outlook and Policy Implications. Vol. 1 (Toronto)

Averch, H. and L. Johnson (1962) 'Behaviour of the firm under regulatory constraint.' American Economic Review 52, 1053-69

Bailey, E.E. (1972) 'Economic theory of regulatory constraint.' Ph.D. dissertation, Princeton University

David, P. (1971) 'The mechanization of reaping in the ante-bellum midwest.' Reprinted in N. Rosenberg, ed., The Economics of Technological Change (Baltimore: Penguin Press) 229-73

Foster, J.S. (1974) 'Engineering in the Canadian nuclear power programme.' Reprinted in Ontario Hydro, Nuclear Energy in Canada (Toronto: IPC Business Press Ltd) 478-80

Globerman, S. (1975) 'Technological diffusion in the Canadian tool and die industry.' Review of Economics and Statistics 57, 428-34

Griliches, Z. (1957) 'Hybrid corn: an exploration in the economics of technological change.' Econometrica 25, 501-22

Hughes, W.R. (1971) 'Scale frontiers in electric power.' Reprinted in W. Capron, ed., Technological Change in Regulated Industries (Washington DC: Brookings Institution) 44-85

Hydro Electric Power Commission of Ontario (1962-77) Ontario Hydro Annual Report (Toronto)

Kennedy, C. and A.P. Thirlwall (1972) 'Technical progress: a survey.' Economic Journal 82, 11-72

Mansfield, E. (1968) Industrial Research and Technological Innovation: An Econometric Analysis (New York: W.W. Norton)

Mansfield, E., J. Rapoport, J. Schnee, S. Wagner, and M. Hamburger (1971) 'The diffusion of a major manufacturing innovation.' In Research and Innovation in the Modern Corporation (New York: W.W. Norton) 186-206

Nelson, R.R. (1972) 'Issues and suggestions for the study of industrial organization in a regime of rapid technical change.' In V.R. Fuchs, ed., Policy Issues and Research Opportunities in Industrial Organization (New York: NBER)

Ontario Hydro (1962-77) Ontario Hydro Statistical Yearbook (Toronto)

- (1977) Generation: Nuclear. Submission to the Royal Commission on Electrical Power Planning, Final Hearings

Ontario Ministry of Energy (1979) Ontario Energy Review (Toronto)

Romeo, A. (1975) 'Interindustry and interfirm differences in the rate of diffusion of an innovation.' Review of Economics and Statistics 57, 311-19

- 'The rate of imitation of a capital-embodied process innovation.' Economica 44, 63-9

Rowan, Malcolm (1978) Canadian Nuclear Policy and Federal-Provincial Relations. Paper by the Deputy Minister of Energy of Ontario

Royal Commission on Electric Power Planning (1978) A Race Against Time (Toronto)

Smith, H.A. (1975) 'Review of the development and status of CANDU nuclear power plant.' Paper prepared for the European Nuclear Conference 1975 (Toronto: Ontario Hydro)

Statistics Canada (1962-77a) Canada Yearbook (Ottawa)
- (1962-77b) Electric Power Statistics: Annual Statistics Vol. 2 (Ottawa)
- (1975-7 Electric Power Statistics: Inventory of Prime Mover and Electric Generating Equipment. Vol. 3 (Ottawa)

Statistics Canada (1976-8) Electric Power Statistics: Annual Electric Power Survey of Capability and Load Vol. 1 (Ottawa)
- (1978) Canadian Statistical Review (Ottawa)

Swain, H., R. Overend, and T.A. Ledwell (1978) Canadian Renewable Energy Prospects (Ottawa: Energy, Mines and Resources)

U.S. Atomic Energy Commission (1971a) The Nuclear Industry (Washington DC)
- (1971b) Status of Central Station Nuclear Power Reactors. Significant Milestones (Washington DC)

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